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Research paper

Factors controlling the petroleum generation characteristics of Palaeogene source rocks in the Austrian Molasse Basin as revealed by principal component analysis biplots

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ABSTRACT

After Rock-Eval & TOC screening and heterogeneity evaluation on 91 Palaeogene source rock samples from a well drilled in the Austrian Molasse Basin, ten shale samples were selected for detailed investigations by means of pyrolysis-gas chromatography, bulk kinetics and biomarker identification and quantification. Afterwards, 2-D biplots based on principal component analysis were applied to unravel the palaeo-environmental control on the development of petroleum source rocks.

All samples are immature source rocks with good petroleum generation potentials. The redox environment during deposition was generally reducing, and palaeosalinity is suggested to be the main factor causing the differences in organic carbon contents among the samples. The hydrogen index values, the gas generation preferences and the aromaticity of the products are controlled by both depositional environment and precursors, and the product of a salinity indicator (MTTC) and the oleanane index is introduced as predictive proxy to evaluate these features. The maturity indicator (Tmax) is revealed as dominated by the stability of the kerogen structure which is controlled by the proportion of organic sulphur compounds in the kerogen. The global Eocene-Oligocene climate change from a greenhouse to an icehouse world is suggested to play an important role in changing the palaeoenvironment and further in influencing the development of petroleum source rocks by triggering upwelling, increasing the palaeo-sea water salinity and decreasing the deposition of carbonate-minerals.

The chemometric method suggested here acts as a powerful tool in identifying the controlling factors for the petroleum generation potential among many variables, and can be applied more widely in petroleum geology when multi-parameters are involved to get quick and meaningful correlations.

1. Introduction

Chemometrics, which is a conceptual approach of processing data with various numerical techniques in order to extract useful information (Kramer, 1998), plays a very important role in geosciences (Hammer et al., 2001). However, the application of chemometric tools, e.g., hierarchical cluster analysis (HCA) or principal component analysis (PCA), in petroleum geology is generally applied in oil-source rock or oil-oil correlation studies (Peters et al., 2007, 2016; Yang et al., 2017). These powerful statistical approaches can not only group samples with similar geological features but also show the correlations of parameters that differentiate the samples. Therefore, there is also a great potential for chemometrics in unravelling the controlling factors for the development of different petroleum generation characteristics when according parameters are used in the analysis.

The Eocene-Oligocene Schöneck Formation and the overlying Dynow Formation in the Molasse Basin are organic-rich marine deposits with some brackish intervals in the uppermost Schöneck Formation and the Dynow Formation. These source rocks are immature toward the Bohemian Massif direction and enter the oil window at ca. 4 km depth beneath the Alpine nappes (Gratzer et al., 2011). They are considered as the main source rocks for a series of oil fields (Gratzer et al., 2011; Véron, 2005) and thermogenic/biogenic gas reservoirs (Pytlak et al., 2016) found in Upper Austria. Previous work on these Palaeogene source rocks in the Molasse Basin has been focused on palaeoceanography (Schulz et al., 2002), spatial architecture (Sachsenhofer and Schulz, 2006), oil-source rock correlation (Gratzer et al., 2011), and basin modelling (Gusterhuber et al., 2014). However, the vertical

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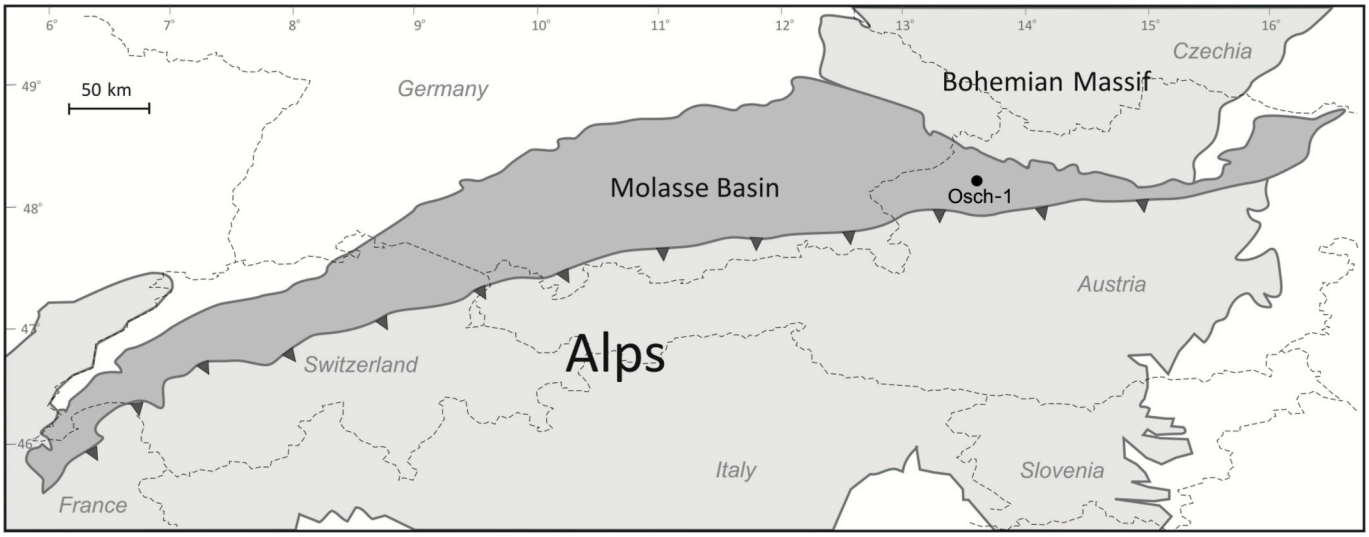

Fig. 1. Geological situation of the Molasse Basin and the location of well Oberschauersberg 1(Osch1).

heterogeneity of the detailed petroleum generation potential has not been systematically investigated yet. For example, there is still a need to gain compositional information of the hydrocarbon potential which is critically important in predicting the physical properties of producing oil (di Primio and Horsfield, 2006) and the bulk kinetic features which play important roles in determining the timing of petroleum generation during basin modelling (Ungerer and Pelet, 1987). In addition, the determination of the geological controls on these petroleum generation characteristics would improve the understanding of the regional petroleum geology and thus provide implications in finding more effective source rocks in similar geological environments.

2. Geological background and samples

The Molasse Basin, which is alternatively termed as Alpine Foreland Basin (Crampton and Allen, 1995; Pfiffner, 1986), extends along the northern margin of the Alps from France to the eastern border of Austria (Fig. 1). This Cenozoic foreland basin is formed from the subduction of the southern margin of the European plate beneath the Adriatic plate (Ziegler and Roure, 1999) and is about 900 km long and up to 120 km wide in the German sector in its present-day configuration (Véron, 2005).

The Eocene-Oligocene Schöneck Formation and the Oligocene Dynow Formation consisting of marlstone, shale and thin carbonates (Fig. 2) were deposited in a marine to brackish environment. The lithological transition was suggested to be induced by the basin subsidence/uplift and water level changes (Báldi, 1984) which is similar to the depositional model in the Black Sea since 7500 years bp (Schulz et al., 2005). The sedimentary succession of the Schöneck and Dynow Formations is regional expression of a wider phenomenon and similar palaeo-environmental signals were stored in the rocks developed in the Paratethys realm. For examples, high total organic carbon (TOC) contents can be traced further to the Eastern Paratethys domain where the contemporaneously deposited Maikop Formation is one of the main source rocks for hydrocarbons found in the South Caspian Basin, the Caucasus region, and the Black Sea Basin (Abrams and Narimanov, 1997; Gürgey, 2003; Sachsenhofer et al., 2017).

An available data set (Schulz et al., 2002) was completed by additional core samples to gain a data base of 91 samples from the borehole Oberschauersberg 1 (Osch-1) (Fig. 1) with TOC and Rock-Eval data. In the following, ten samples were selected as key representatives of different facies for detailed investigations (Fig. 2). Previous investigations focussed on lithology, stratigraphy, and isotopes of this well (Schulz, 2003). The lower part of Schöneck Formation is mainly composed of marlstone with very thin dolomite and volcanic ashes interlayers (Schulz, 2003), while the upper part is featured by carbonate-free claystone with two marlstone interlayers (Fig. 2). Three depositional cycles were identified in the overlying Dynow Formation (Schulz et al., 2004), two of which are shown in Fig. 2, i.e., the two limestone layers interbedded in the marlstone represent the deposition during highstand systems tracts or massive influx of nutrient-loaden freshwater.

3. Methods

Powdered samples were analysed for total carbon (TC), total organic carbon (after acidification) and total sulphur contents using a Leco CS-225 analyser after acidification to remove carbonate. The differences between TC and TOC is the total inorganic carbon (TIC). Calcite contents were calculated by multiplying 8.33 with TIC (Espitalié et al., 1977). Rock-Eval pyrolysis was performed using Rock-Eval 6 following established procedures (Behar et al., 2001).

Pyrolysis-GC (PyGC) was performed using the Quantum MSSV-2 Thermal Analysis System interfaced with an Agilent GC-6890A. About 10 mg of coarsely crushed reference shale was filled into a small open glass tube and heated at 300 °C for 3 min to vent the free hydrocarbons. Hydrocarbons generated between 300 and 600 °C were collected and measured. Quantification of individual compounds was conducted by external standardisation with n-butane.

Bulk kinetic parameters were assessed by subjecting samples to open-system, non-isothermal pyrolysis at four different linear heating rates (0.7, 2, 5, 15 °C/min) using a Source Rock Analyser® (SRA) following established procedures (Yang and Horsfield, 2016). The discrete activation-energy distribution optimization with a single variable frequency factor as well as geological extrapolation was carried out using the KINETICS 2000® and KMOD® programs.

Soxhlet extraction was carried out on powdered shale samples for 24 h at 50 °C using dichloromethane and methanol mixture (99:1) as solvent. After asphaltene precipitation, the maltenes were separated into aliphatic, aromatic hydrocarbons, and NSO fractions by medium-pressure liquid chromatography (MPLC) fractionation as described by (Radke et al., 1980). Gas chromatography with flame ionization detector (GC-FID) was carried out on the aliphatic hydrocarbon fractions. The instrument was equipped with a HP Ultra 1 capillary column. The oven temperature was programmed from 40 °C to 300 °C with a 5 °C/min heating rate. GC-MS test runs were based on a Trace GC Ultra system coupled to a DSQ mass spectrometer. The GC was equipped with a PTV injection system and a fused silica capillary column, and was heated from 50 °C to 310 °C at a rate of 3 °C/min.

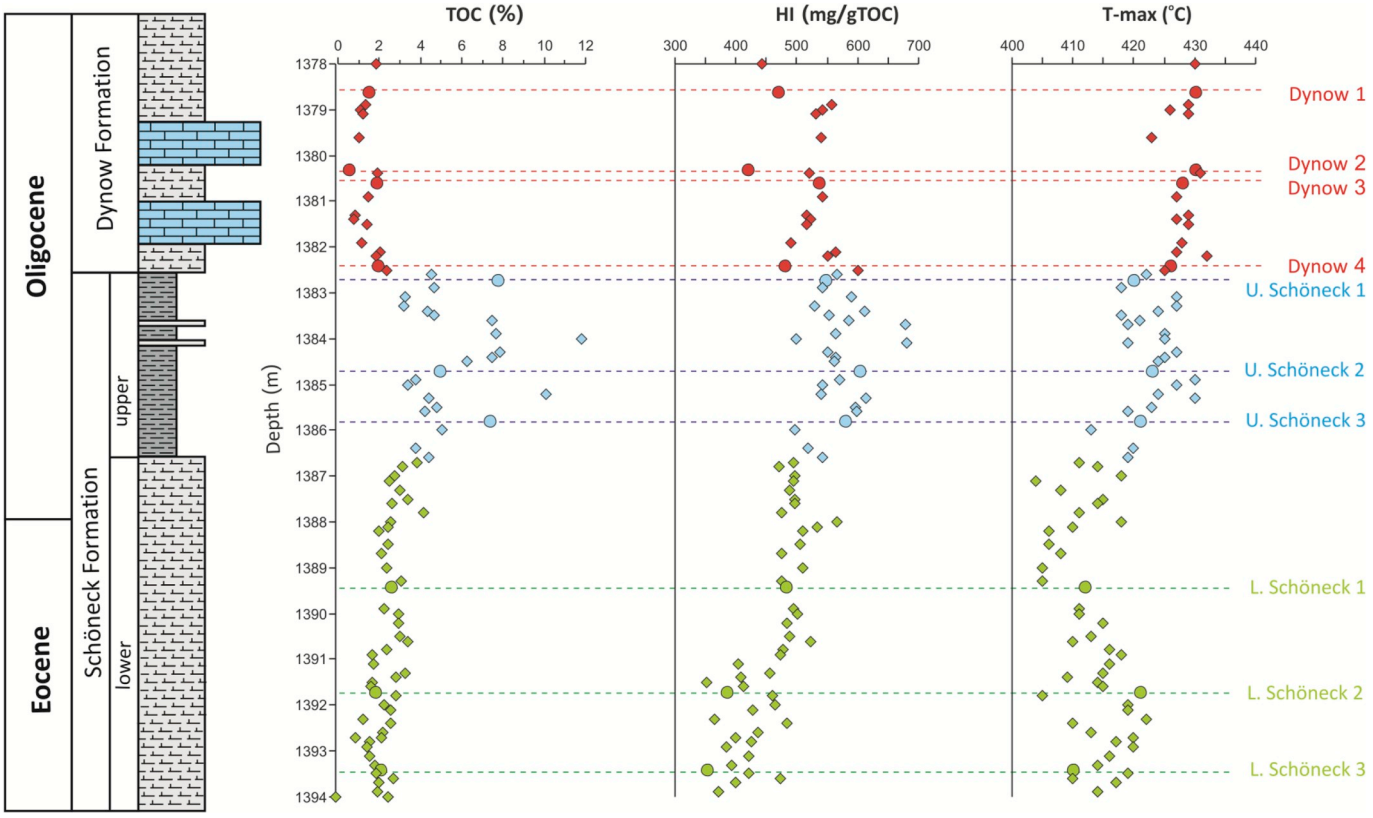

Fig. 2. Simplified stratigraphy of the Schöneck Formation and Dynow Formation in well Oberschauersberg 1. 10 representative samples (circle) were selected to carry out more detailed research based on the Rock-Eval and TOC screening of the 91 samples (rhombus). Sample numbers of the selected samples are listed on the right part of the figure.

The hierarchical cluster analysis and principal component analysis are carried out with the PAST statistical programme which is designed for geological research (Hammer et al., 2001). All parameters were normalized to the same scale by using the "correlation matrix" option, so that the variations among different parameters are comparable.

4. Results

4.1. Screening data

Rock-Eval and TOC data as fundamental parameters basically provide information about the organic matter richness, quality, and maturity of the potential source rocks (Table 1). Most of the Dynow Formation samples contain TOC contents between 1% and 2% (Fig. 2) and can be classified as "Good Source Rock" based on the criteria suggested by Peters and Cassa (1994). The Schöneck Formation samples are featured by much higher organic contents, and the upper part and lower part can be viewed as "Excellent Source Rock" (TOC > 4%) and "Very Good Source Rock" (2% < TOC < 4%), respectively (Peters and Cassa, 1994). With 300 mg/gTOC < HI < 600 mg/gTOC, most samples contain type II kerogen (Espitalie et al., 1977). The Upper Schöneck Formation has exceptionally high hydrogen index (HI) values compared with the other intervals whereas the lower part of the Schöneck Formation is featured by relatively lower HI values (Fig. 2). All samples are characterized by T_{max} values lower than 435 °C (Fig. 2) and are thermally immature. This conclusion is consistent with previous work which suggest the vitrinite reflectance is lower than 0.35% (Schulz et al., 2002). The average T_{max} values show a decrease from the Dynow Formation to the Lower Schöneck Formation. This trend is neither a reflection of the geological burial history which would suggest a higher thermal maturity of older rocks, nor a bitumen suppression on T_{max} which occurs in high TOC or high HI intervals (Snowdon, 1995).

In brief, the Schöneck and Dynow Formations are natural laboratories with considerable immature organic matter. These intervals can be effective petroleum source rocks at suitable maturity, and are characterized by organic geochemical heterogeneities on decimeter scales (Fig. 2). Nevertheless, the three rock units can still be differentiated by their featured Rock-Eval and TOC data. This enables the selection of 10 key samples as representatives of the three intervals (Fig. 2) to show their individual petroleum generation characteristics depended on their palaeoceanographic history.

4.2. Pyrolysis-gas chromatography

The PyGC analysis of source rocks is a technique that provides a quick evaluation of the kerogen structure (Dembicki et al., 1983; Van de Meent et al., 1980) and relates the structural information to the potential bulk petroleum composition by means of petroleum type organofacies (Horsfield, 1989).

In the Upper Schöneck samples, both gas and oil (up to C_{26}) compositions can be identified (Fig. 3B). In comparison, high molecular hydrocarbons in the Dynow Formation and Lower Schöneck Formation are less abundant (Fig. 3A and C). Therefore, the petroleum that can be generated in these intervals is predicted as Paraffinic-Naphthenic-Aromatic Oil with low wax content, while the Upper Schöneck samples may generate oil with high wax contents (Fig. 4A). When the gas chromatographic signals between C_8 and C_{10} are focused (Fig. 3), the Upper Schöneck samples are featured by relatively low concentrations of aromatic compounds compared with neighbouring aliphatic hydrocarbons, while the Lower Schöneck samples generate much higher

Table 1
A compilation of geochemical parameters used in the research. The * marked parameters were applied in the chemometric analysis as shown in Fig. 10. For PyGC data, the first six columns show the data used in Fig. 4 A and B, three for each. $GeoT_{max}$ values were achieved by differentiating the geological transformation curves in Fig. 5. For biomarkers, "H" stands for hopanes, "O" represents oleanane, and "St" is short for steranes.

Samples	Depth (m)	LECO combustion and Rock-Eval								PyGC				
		TOC (%)*	TOC/S*	TIC	Carb (%)	S1 (mg/g)	S2 (mg/g)	Tmax (oC)*	HI (mg/g TOC)*	C1-5 Bulk*	nC6-14 Res.	nC15 +- Res.	2,3-dmThiophene	n-nonene; 9:1
Dynow 1	1378.6	1.5	1.9	5.84	48.7	0.1	7.03	430	468.7	74.00%	18.50%	7.50%	11.40%	44.40%
Dynow 2	1380.3	0.52	1.81	9.98	83.2	0.02	2.19	430	420.2	73.70%	19.80%	6.50%	10.70%	44.20%
Dynow 3	1380.6	1.84	2.02	7.12	59.3	0.12	9.85	428	535.1	70.00%	19.80%	10.10%	11.60%	49.00%
Dynow 4	1382.4	1.92	4.68	10.47	87.2	0.17	9.2	426	479	70.40%	20.00%	9.60%	10.90%	47.30%
U.Schöneck 1	1382.7	7.75	2.52	0.29	2.4	1.08	42.34	420	546.3	62.00%	22.50%	15.50%	12.60%	54.70%
U.Schöneck 2	1384.7	4.95	0.9	0.1	0.8	1.12	29.8	423	602.1	58.00%	26.00%	16.00%	11.60%	57.40%
U.Schöneck 3	1385.8	7.34	2.05	0.08	0.7	1.02	42.5	421	579	60.40%	25.70%	13.90%	11.60%	56.80%
L.Schöneck 1	1389.4	2.56	1.19	5.5	45.8	0.17	12.33	412	481.6	75.00%	18.70%	6.30%	23.70%	34.80%
L.Schöneck 2	1391.7	1.77	0.67	1.66	13.8	0.14	6.82	411	385.2	75.20%	17.80%	7.00%	31.30%	36.00%
L.Schöneck 3	1393.4	2.05	0.93	0.21	1.7	0.09	7.23	410	352.7	79.70%	16.90%	3.50%	25.00%	32.90%

Samples	PyGC			Bulk kinetic	GC-FID	GC-MS									
	o-xylene	o-Xyl/C9*	2,3-dMT/C9*	GeoTmax (oC)*	Pr/Ph*	C25HBI/C21*	OL/(OL + H)*	C31H/C30H*	C35H/C34H*	St/H*	St 27*	St 28*	St 29	MTTC ratio*	OL index*MTTC
Dynow 1	44.10%	0.99	0.26	153	2.93	0	0.11	0.49	0.75	0.93	26.40%	38.50%	35.10%	0.82	0.092
Dynow 2	45.00%	1.02	0.24	154	2.15	0	0.1	0.39	0.97	1.18	20.40%	45.80%	33.80%	0.98	0.096
Dynow 3	39.40%	0.8	0.24	153	2.18	0	0.14	0.4	1.03	1.04	23.20%	40.50%	36.30%	0.72	0.1
Dynow 4	41.80%	0.88	0.23	151	2.35	0	0.11	0.44	1.01	0.76	25.70%	38.40%	35.90%	0.75	0.083
U.Schöneck 1	32.70%	0.6	0.23	148	1.12	0.58	0.09	0.64	1.51	0.7	35.00%	30.00%	35.00%	0.57	0.053
U.Schöneck 2	31.00%	0.54	0.21	147	1.62	0.51	0.06	0.67	1.74	0.68	32.40%	34.50%	33.10%	0.61	0.039
U.Schöneck 3	31.60%	0.56	0.2	149	1.13	0.52	0.08	0.65	1.61	0.65	33.50%	30.70%	35.80%	0.59	0.048
L.Schöneck 1	41.50%	1.19	0.68	143	1.22	0.41	0.24	0.63	2.21	2.23	39.10%	28.10%	32.80%	0.63	0.153
L.Schöneck 2	32.70%	0.91	0.87	134	1.91	0.34	0.2	0.59	1.86	1.65	38.40%	27.30%	34.30%	0.87	0.176
L.Schöneck 3	42.10%	1.28	0.76	136	2.2	0.36	0.3	0.73	2.15	2.15	37.70%	27.70%	34.70%	0.79	0.238

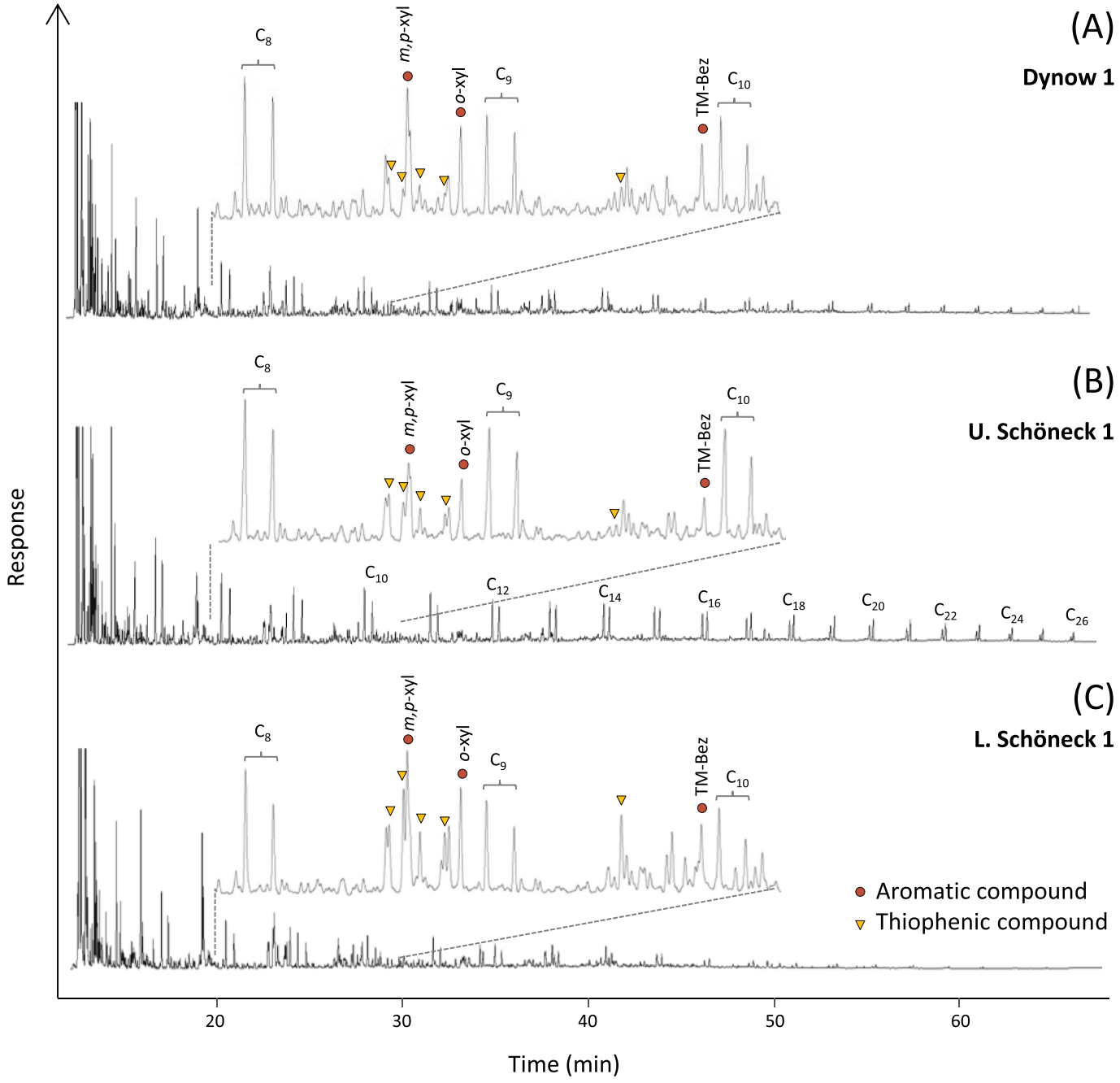

Fig. 3. PyGC traces of the three source rocks. Aliphatic hydrocarbon doublets are marked by carbon numbers. Aromatic compounds listed in the figures are *meta*-, *para*-xylene, *ortho*-xylene, and 1, 2, 4-Trimethylbenzene, respectively. Thiophenic compounds include, from left to right, 2-Ethylthiophene, 2,5-Dimethylthiophene, 2,4-Dimethylthiophene, 2,3-Dimethylthiophene, and 2-Ethyl-5-Methylthiophene.

thiophenic compounds than the rest two intervals. These features become obvious in Fig. 4B where diagnostic compounds are used as end members in the ternary diagram. Although, kerogen from all samples can be viewed as type II, the differences in aromaticity and sulphur content of each layer can be clearly identified.

4.3. Bulk kinetics

The average activation energy distribution and frequency factors of the Lower Schöneck samples are lower and smaller than the other two intervals (Fig. 5). In addition, the peak activation energy of Lower Schöneck Formation is lower than the Upper Schöneck Formation which may indicate a more heterogeneous kerogen structure. The geological extrapolation provides a more direct comparison between the samples (Fig. 5). The Lower Schöneck Formation is thus predicted to generate hydrocarbons at much lower temperature than the other two intervals, and the differences in kerogen kinetic stability can also be identified by the geological T_{max} values (Table 1) which were achieved by differentiating the geological transformation curves in Fig. 5.

4.4. Biomarkers

The pristane/phytane ratios (Pr/Ph) of all samples are in the range of 1.1–3.0 (Table 1) which generally imply that they were neither deposited in extremely reducing nor very oxidizing environments. However, inferences from Pr/Ph on redox environment or palaeosalinity should be supported by other geochemical data (Peters et al., 1999).

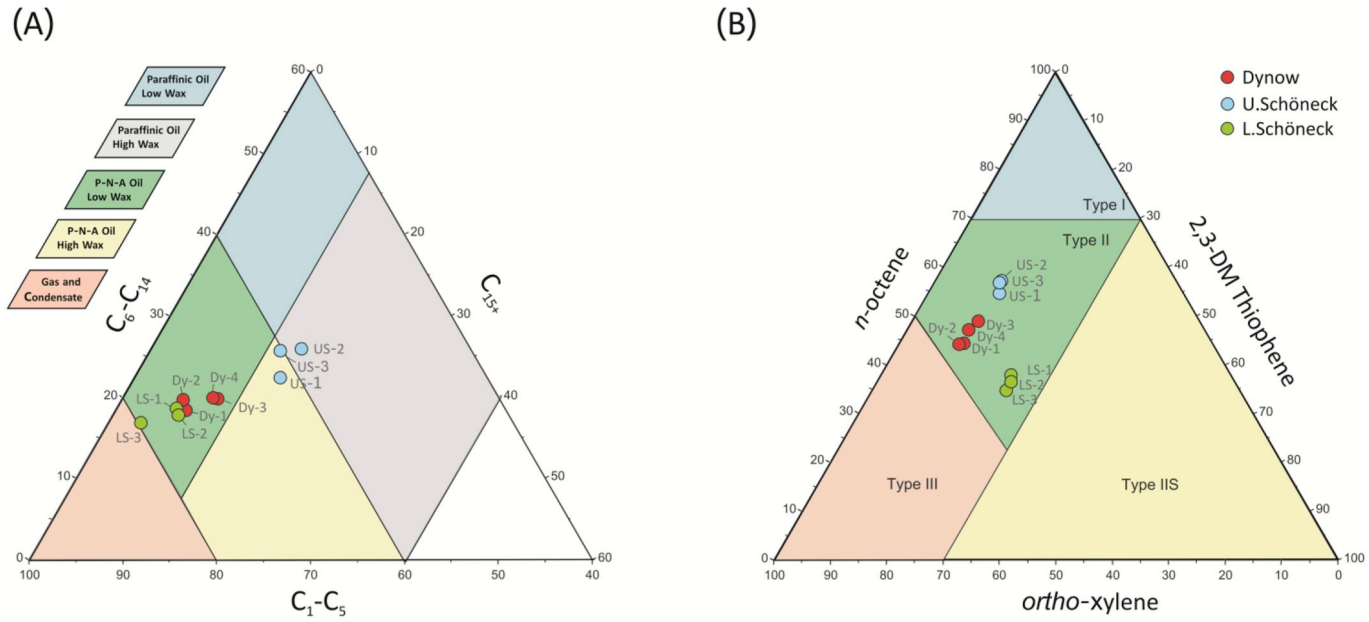

Fig. 4. Ternary diagrams of the pyrolysates for interpretations of organic facies and kerogen structures of the samples.(A) Petroleum products prediction based on chain-length distribution (Horsfield, 1989) and (B) organic type classification based on diagnostic aliphatic, aromatic, and thiophenic compounds (Eglinton et al., 1990).

C_{25} highly branched isoprenoids (C_{25}HBI), which are sourced from benthic (Volkman et al., 1994) or planktonic diatoms (Belt et al., 2001), can be identified in the Schöneck Formation (Fig. 6). A relative comparison between the C_{25}HBI and the neighbouring *n*-C_{21} alkane manifests that the Upper Schöneck contains much more abundant C_{25}HBI than the lower part (Table 1 and Fig. 6). The relative content ratio of steranes/hopanes in the Lower Schöneck Formation is obviously higher than the other two intervals (Table 1 and Fig. 6). This

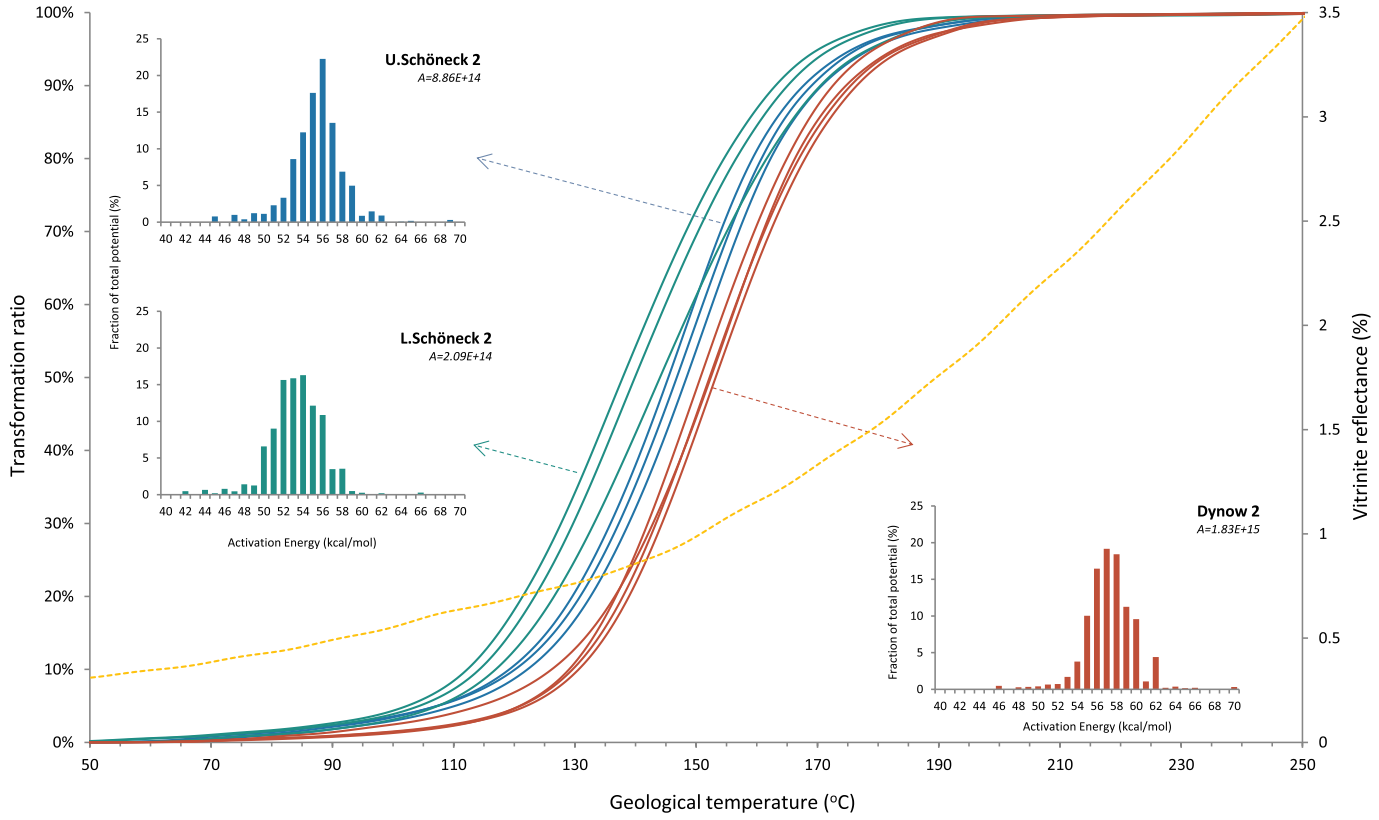

Fig. 5. The geological extrapolation (heating rate of 3 K/million year) of the bulk kinetic parameters. Three end member samples are shown by detailed activation energy distribution and frequency factors. The yellow dot line depicts the calculated vitrinite reflectance based on EASY%Ro method (Sweeney and Burnham, 1990). The calculated $GeoT_{max}$ for each sample can be found in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

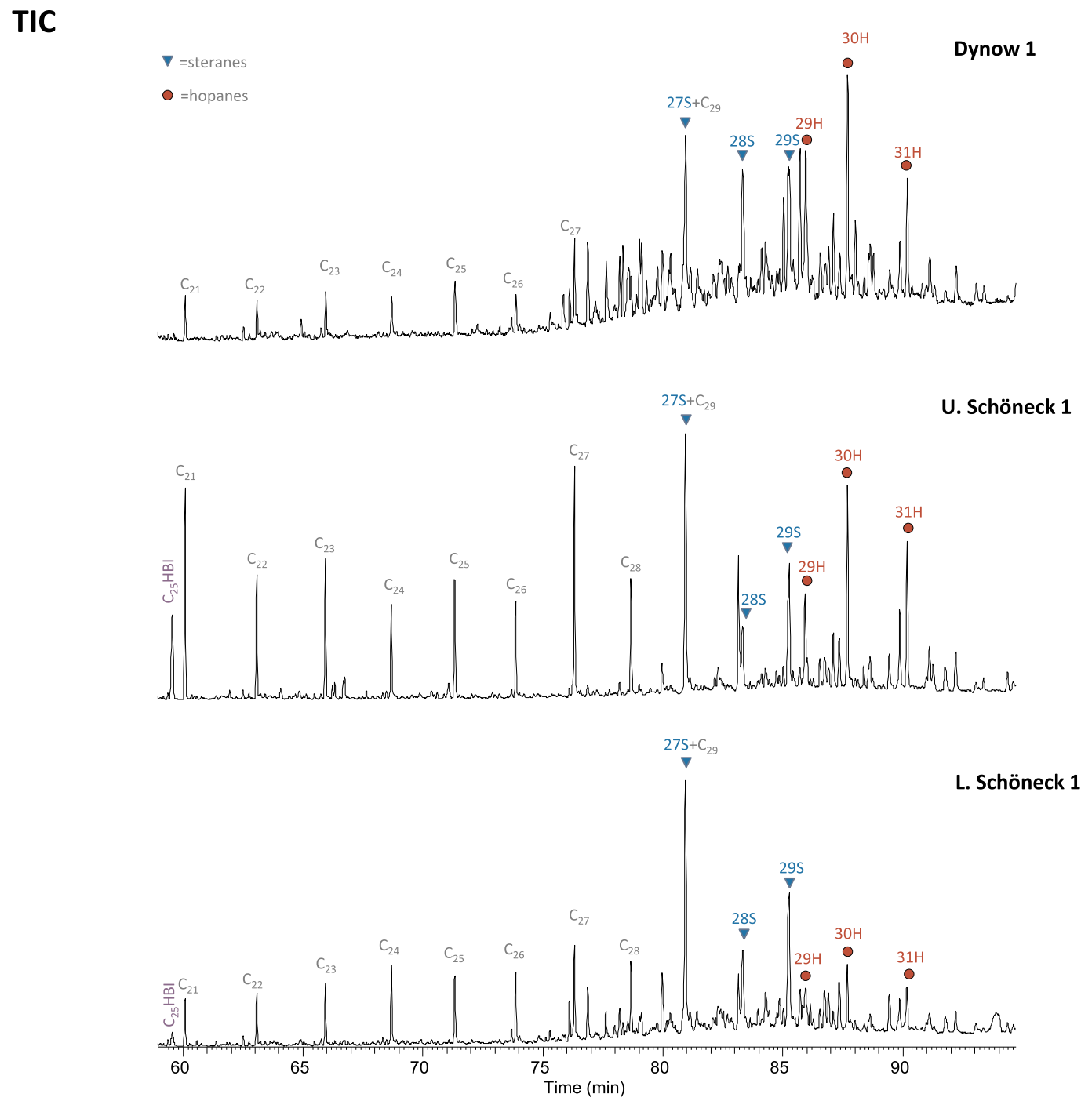

Fig. 6. Total ion chromatogram traces of three end member samples. Saturated hydrocarbons are shown by carbon numbers. Sterane and hopanes are marked by carbon numbers plus "S" and "H", respectively.

would imply that the Lower Schöneck Formation has a higher dominance of eukaryotes (mainly algae and higher plant) over prokaryotes (bacteria) as organic matter input during deposition (Mello et al., 1988).

The distribution of hopanes in the three intervals is different (Fig. 7A). The relative contents of C_{35} homohopane and oleanane decrease from the Lower Schöneck Formation up to the Dynow Formation. Accordingly, the 17α-diahopane which is normally correlated with oleanane (Li et al., 2009) is enriched only in the lower part of the Schöneck Formation (Fig. 7A). In addition, unsaturated biomarkers, e.g., norneohop-13(18)-ene and olean-13(18)-ene, can be identified based on retention times and fragment mass information (Curiale and Bromley, 1996; Sinninghe Damsté et al., 2014). The concentrations of tricyclic terpanes are generally low in all samples, because they are not readily released from the kerogen at this level of maturity (Seifert and Moldowan, 1978).

The C_{27}—C_{30} steranes are dominated by ααα R isomers (Fig. 7B) due to the low organic matter maturity (McKenzie et al., 1983). Obviously, the relative contents of C_{27} and C_{30} steranes in the Dynow Formation are much lower than in the other intervals and indicate a shallower marine environment than during deposition of the Schöneck Formation (Fig. 8).

In the aromatic fraction of biomarkers, four alkylated methyl-trimethyl-tridecyl-chromans (MTTCs), which are derived from eu-bacteria

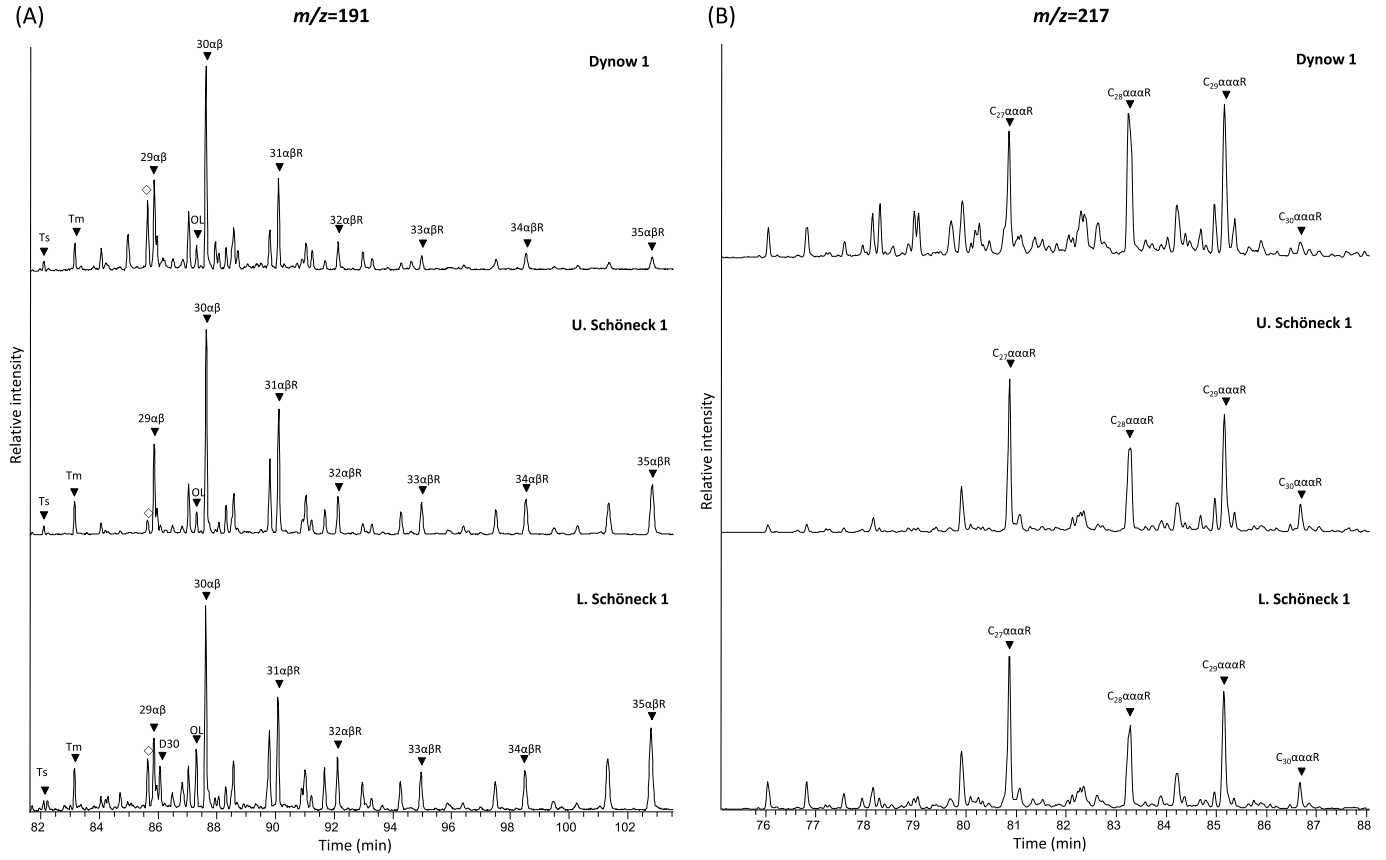

Fig. 7. Comparison of hopane (A) and sterane (B) traces of three representative samples. Ts = 18α-trisnorneohopane; Tm = 17α –trisnorhopane; D30 = 17α-diahopane; OL = oleanane. The diamond marked peak in (A) is norneohop-13(18)-ene for Dynow Formation, and it is co-elution of norneohop-13(18)-ene and olean-13(18)-ene for Schöneck samples.

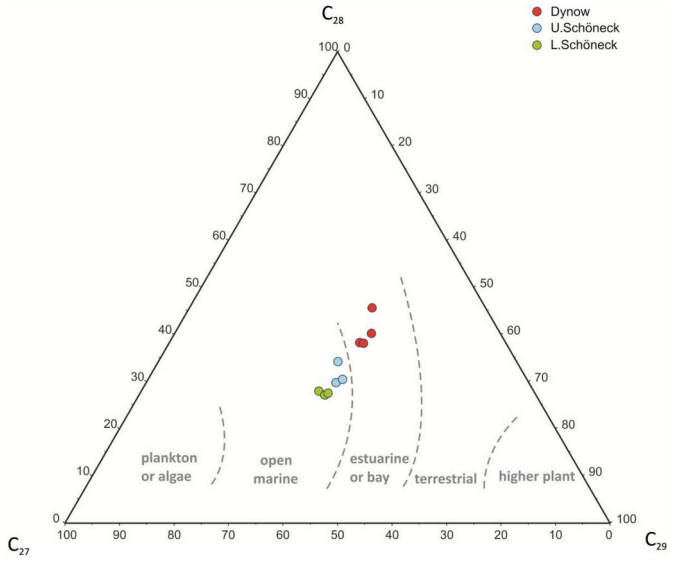

Fig. 8. Ternary diagram showing the relative distribution of ααααR C_{27}, C_{28}, and C_{29} steranes (Huang and Meinschein, 1979).

and archaea (Damsté et al., 1987) or are formed via the condensation of chlorophyll and alkylphenols (Li et al., 1995), can be detected in the Schöneck Formation (Fig. 9). The distributions of the methylated MTTCs indicate salinity changes of the surface water of a density stratified water column, i.e. the value of MTTC ratio (defined as trimethyl-MTTC/sum of the four alkylated MTTC) is negatively correlated with palaeosalinity (Sinninghe Damsté et al., 1993). By the absence of 8-methyl-MTTC, the Dynow Formation samples have higher MTTC ratios than Schöneck Formation (Fig. 9). Within the Schöneck Formation, the upper part has less profound dominance of trimethyl-MTTC which implies a high palaeosalinity.

5. Discussion

5.1. Chemometric analyses

To elucidate the controlling factors for the different petroleum generation features of the three intervals, diagnostic geochemical parameters (listed in Table 1) were used to carry out the chemometric analyses. The general result is that the three source rocks can be clearly separated from each other in the HCA (Fig. 10A) and PCA (Fig. 10B). More importantly, the biplots which demonstrate how the samples are differentiated from each other show correlations between screening parameters (Rock-Eval, TOC and sulphur content), pyrolytic features (PyGC and bulk kinetics), and biomarkers (Fig. 10B). It needs to be noticed that a certain percentage of interpreted total variance by PC1 and PC2 is required for a reliable interpretation of the biplots (an empirical minimum lower limit for this is suggested to be 80% here).

It can be observed that the Lower Schöneck Formation is different from the other two intervals by very low T_{max} values whereas the Upper Schöneck Formation is featured by high TOC contents and HI values (Fig. 10B) which are consistent with Fig. 2. In 2-dimensional PCA biplots, the lengths of the vectors estimate the standard deviations of the respective variables and the cosine values of angles between vectors approximate the intervariable correlations (Aitchison and Greenacre, 2002). In other words, parameter vectors at 0° or 180° angles are highly correlated (either positively or negatively), while those being mutually perpendicular vectors are generally independent from each other.

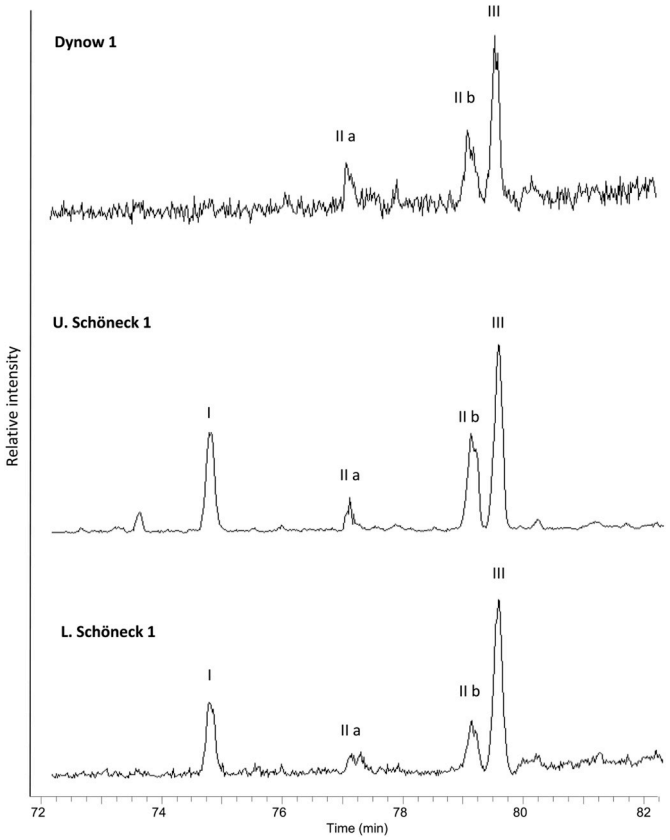

Fig. 9. Mass chromatograms of m/z 107 + 121 + 135 + 149 revealing the distributions of the methylated MTTCs. I = 8-methyl-MTTC; II a = 7,8-dimethyl-MTTC; II b = 5,8-dimethyl-MTTC; III = 5,7,8-trimethyl-MTTC.

5.2. TOC enrichment

Productivity (Pedersen and Calvert, 1990; Totman Parrish and Curtis, 1982), preservation (Demaison, 1991; Demaison and Moore, 1980), and sedimentation rate (Creaney and Passey, 1993; Ibach, 1982) are typically considered as the most important factors controlling the organic matter richness in petroleum source rocks (Littke et al., 1997). Many examples demonstrate that one factor alone is generally insufficient to yield organic carbon-rich and oil-prone sediments (Katz, 2005), and the thresholds of the aforementioned factors in the investigated samples thus have to be reached. The vectors of TOC and MTTC ratios are roughly at 175° (Fig. 10B) which implies a negative correlation between these two parameters, and this can be confirmed by Fig. 11A. Therefore, samples with high TOC contents are associated with a high salinity depositional environment (MTTC ratio inversely correlates with palaeosalinity). In addition, the generally negative correlation between TOC contents and Pr/Ph ratios (Fig. 11B) is reflected by the wide angle between these two vectors (Fig. 10B). It seems that Pr/Ph of the investigated samples is a reflection of palaeosalinity (ten Haven et al., 1987) and associated redox conditions in the bottom water (Didyk et al., 1978). The salinity influence on TOC enrichment is also supported by previous research, e.g., the TOC contents of the Laney member of the Green River Shale which was deposited in alkaline water is significantly higher than in the freshwater deposits of the Luman Tongue Green River shale (Horsfield et al., 1994).

The difference in palaeosalinity is perhaps a comprehensive representative of the variations in productivity, redox environment, and sedimentation rate to some degree. Marine environments with low salinity (brackish water) are normally influenced by freshwater fluxes from the landside. Depending on the intensity of the flux, a variability of salinity gradients will be induced. For the depositional time slice of the Lower Schöneck Formation, bottom water anoxia was probably induced by salinity stratification. However, at the same time the supply of the re-mineralized nutrients to the sea surface, particularly nitrate and phosphate in dissolved form, would have been strongly hindered by the halocline (Widayat et al., 2016), and thus the primary productivity also decreased significantly. When it came to the deposition of Upper Schöneck Formation, the Paratethys started isolating from the Tethys Ocean in response of the strong tectonic activity and a small but constrained basin was formed (Báldi, 1984). Contemporaneously, the Eocene-Oligocene glaciation caused a temperature drop (ca. 11 °C), whereas humidity, stratification, bottom water anoxia, and salinity increased within the Paratethys realm (Sotak, 2010; van der Boon et al., 2018). This multifactorial scenario set the scene to enable the deposition of Upper Schöneck Formation with favourable conditions for the preservation of sediments with high TOC contents. In the case of the Dynow Formation, much more fresh water was induced to the shelf regions, and thus the formerly prevailing water stratification and anoxia collapsed. The less reducing environment coupled to high sedimentation rates led to less organic matter preservation due to oxidation and dilution.

It is important to note that a correlation between salinity and organic matter enrichment may exist if only the depositional environment is generally reducing and when a certain level of productivity is reached, otherwise the salinity could be a minor factor. Also, extremely high salinity environments are not *per se* suitable depositional realms for the deposition of successful petroleum source rock, e.g., evaporites which are typically deposited in hypersaline environment can be featured by low organic carbon contents and very low pyrolysis yields (Katz et al., 1987).

5.3. Hydrocarbon generation potential

The HI and the composition of pyrolysates together define the quantity and quality of the hydrocarbons that can be generated from the source rock. The negative correlations between the HI values and the gaseous and aromatic compounds generated in PyGC (Figs. 10B and 12A) are consistent with previous findings (Mahlstedt, 2012; Yang and Horsfield, 2016) and reflect the structural features of the kerogen. It seems that there is no single palaeoenvironmental parameter which directly controls the HI values and the pyrolysate composition. However, the oleanane index (OL index) and the MTTC ratio may both affect these quality indicators as suggested by the biplots (Fig. 10B). Considered as an indicator of flower plants (Moldowan et al., 1994), the OL index reflects the influence of such precursors on the hydrocarbon generation potential, i.e., a higher input of terrestrial advanced plants may decrease the HI (Fig. 12B). The general correlation between salinity and HI (Fig. 12C) is linked with the environment during the process of selective preservation of the organic matter in forming kerogen (Tegelaar et al., 1989). Intense reworking of liptinite can take place in aquatic sedimentary systems and bacterial material can be added to the organic matter, and thus a higher ratio of vitrinite (leading to low HI) can be preserved (Vandenbroucke and Largeau, 2007).

The vectors of the OL index and MTTC plot at similar angles with HI, but toward very different directions (Fig. 10B). Therefore, the combination of these two parameters can compensate their respective deviations from HI and provides a much higher correlation (Fig. 12D). The OL index*MTTC suggested here takes both precursor and depositional environment into account in evaluating the controlling factors of hydrocarbon generation potential, and can be applied in other study areas with similar geological situations.

5.4. Controls on maturity

The maturity indictor T_{max} is obviously controlled by kinetic features of the kerogen (GeoTmax) (Figure 10B and 13A). At the same time, the kinetic stability of the kerogen is highly correlated with the

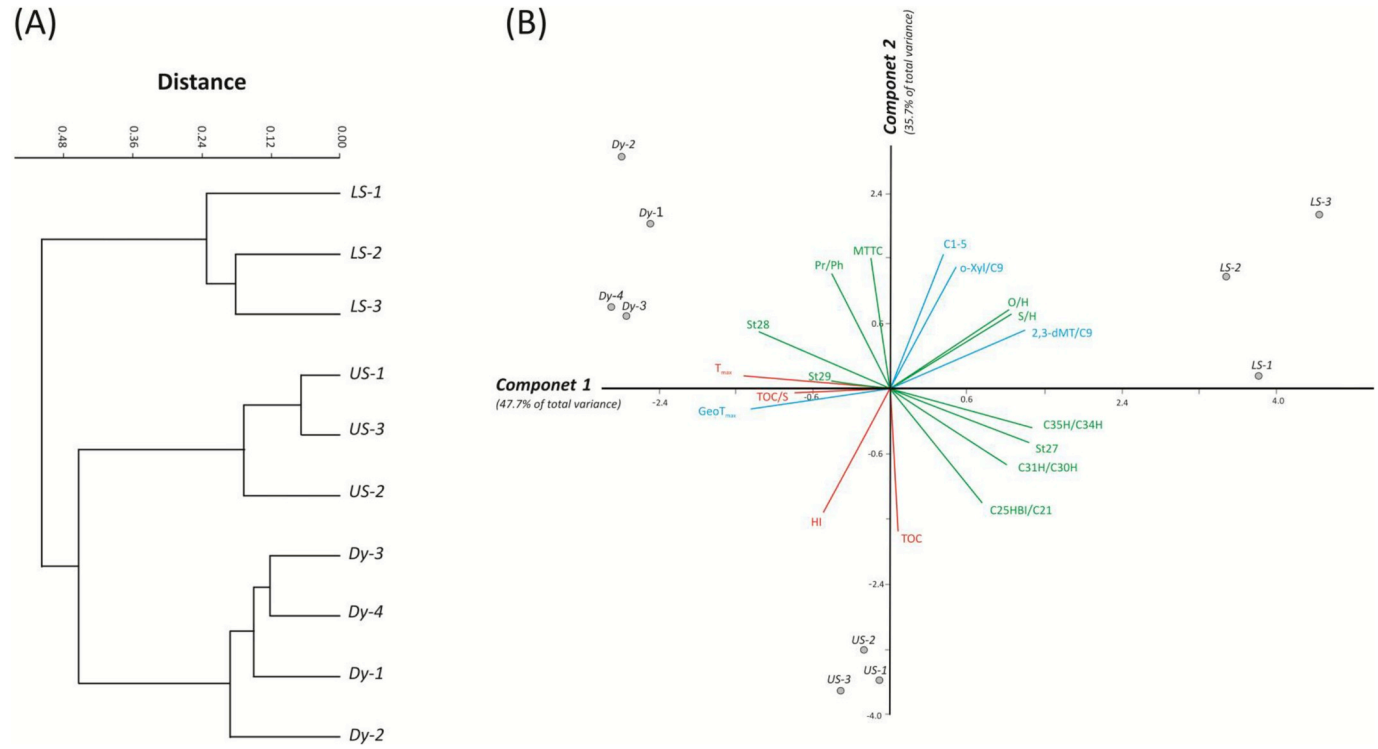

Fig. 10. Chemometric analysis on the 10 source rock samples (Dy = Dynow, US = Upper Schöneck, and LS = Lower Schöneck). Geochemical parameters used as inputs were listed in Table 1. (A) Three group can be clearly separated from each other by the hierarchical cluster analysis. (B) 2-dimensional principal component analysis show how the three groups of samples are differentiated from each other and the correlations between screening data (marked in red), pyrolytic data (marked in blue) and biomarkers (marked in green) can be revealed by the biplots. Component 1 and component 2 together have interpreted 83.44% of the variances among the samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

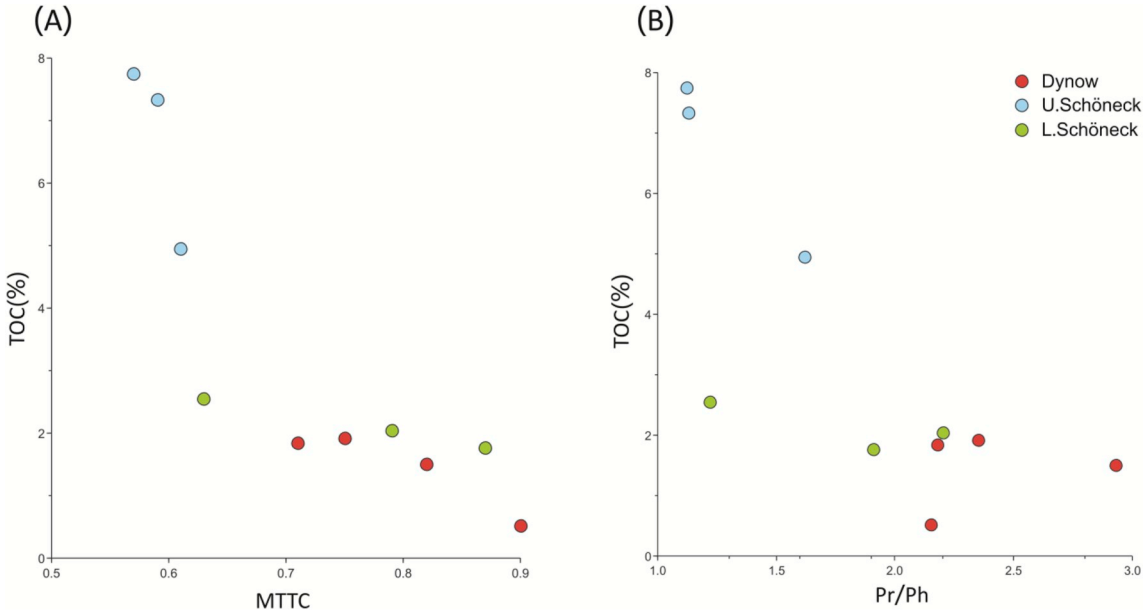

Fig. 11. (A) TOC is negatively proportional to alkylated methyl-trimethyl-tridecyl-chromans (MTTC) ratio. (B) TOC is also generally negatively correlated with pristane over phytane ratio.

relative content of 2, 3-dimethylthiophene generated via pyrolysis (Figure 13B) which is a reflection of the abundance of organic sulphur (Eglinton et al., 1990). The sulphur content of the sediments occurs as inorganic bound sulphur (e.g. in pyrite) and as organic sulphur, which was incorporated into the macromolecular sedimentary organic matter from abiogenic sulphur sources during early diagenesis (Morse and Berner, 1995). Organic bound sulphur decreases the kerogen stability because of either the relative weakness of C–S bonds (Orr, 1986) or sulphur radicals which allow the thermal cracking of C–C bonds to occur at a faster rate and lower thermal stress (Lewan, 1998).

In the Molasse Basin, the unique depositional environment of the shaly to marly Lower Schöneck Formation (dysoxic bottom water with

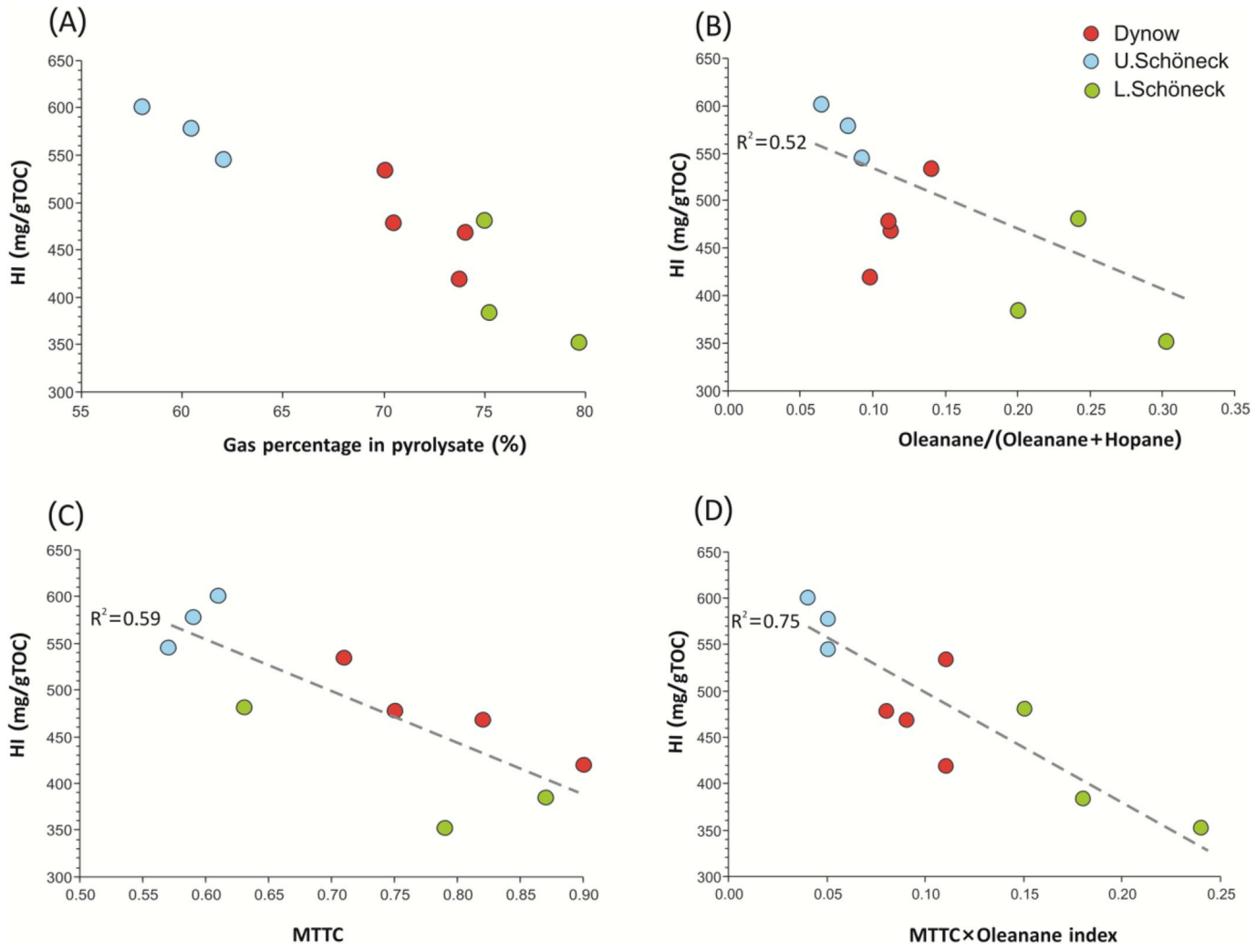

Fig. 12. Hydrogen index (HI) is highly correlated with the relative percentage of gas in the pyrolysate (A). The correlations of HI vs. oleanane index (B) and HI vs. MTTC (C) are much lower than the correlation of HI vs. the product of MTTC and oleanane index (D).

sufficient sulphate supply from the surface water by diffusion) led to the organic sulphur enrichment. These compounds caused the pyrolysates to be rich in alkylated thiophenes lowering the kinetic stability of the kerogen and thus decreasing the T_{max} values. In comparison, more ferric iron was available by continental run-off during the deposition of Upper Schöneck Formation (Schulz et al., 2002). In the anoxic bottom water, sulphate was reduced to sulfide and was bounded in pyrite as inorganic sulphur rather than in kerogen as organic sulphur.

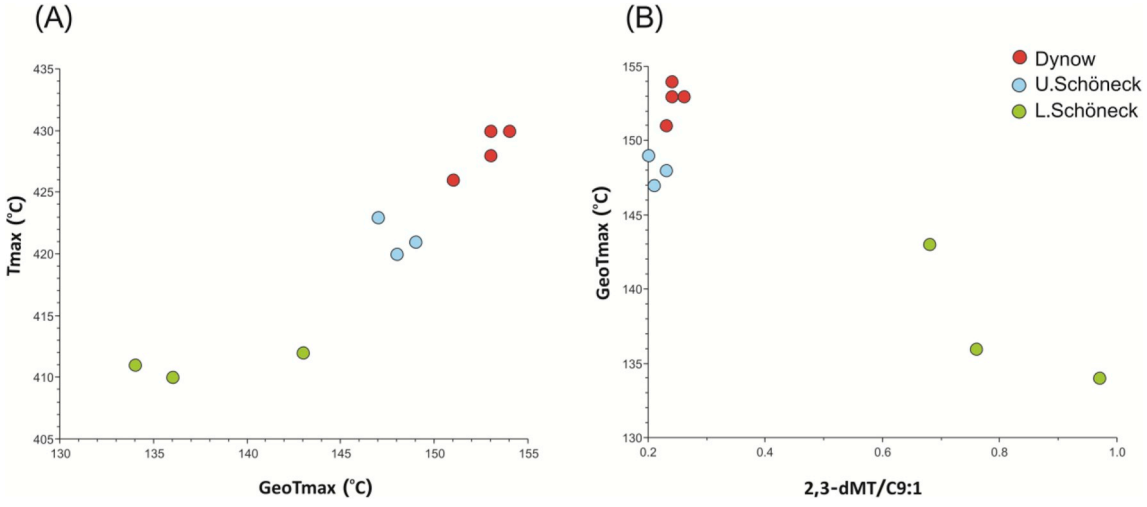

Fig. 13. The control of organic sulphur on maturity.

5.5. Possible impact from climate change at the E/O boundary

The Upper Schöneck Formation which possesses the best petroleum generation potential was generally developed after the initiation of the Antarctic glaciation around the Eocene-Oligocene boundary which caused a global change from a greenhouse to an icehouse world (Savin et al., 1975; van der Boon et al., 2018). Recent palaeoceanographic research on the $\delta^{18}O$ and $\delta^{13}C$ data of foraminifera reveals that the globally established temperature change trend across the E/O boundary can also be recognized in the Paratethys realm (Ozsvart et al., 2016). Besides the local tectonic movements and sea level change, the impact of glaciation-induced cooling on the deposition of the petroleum source rock in the Molasse Basin should be highlighted (Parrish, 1982).

Upwelling phenomena may be triggered during glacial periods because of a combination of stronger and more persistent winds, more extreme thermal gradients, and intensified oceanic circulation patterns (Kennett, 1982). Within the Paratethys, upwelling was suggested to be contemporaneously developed with the E/O boundary glaciation by previous studies (Gier, 2000; Vetö, 1987; Wagner, 1998). It was also reported that the upwelling off northern California (Sancetta et al., 1992) and off eastern New Zealand (Nelson et al., 2000) have both been enhanced by the last glaciation. When the investigated Upper Schöneck Formation was deposited, the shoreline lay in the north (Schulz et al., 2004) and the nearshore wind came from the west and paralleled the coast (von der Heydt and Dijkstra, 2006). These factors meet the prerequisites for the initiation of a wind-driven upwelling system (Sarhan, 2000). This hypothesis is supported by the high concentration of C_{25} HBI in Upper Schöneck Formation (Fig. 6) which denotes a diatom flourishing (Belt et al., 2001) and can be typically observed in the modern Peru upwelling (Volkman et al., 1981) and the Arabian Sea upwelling regions (Wakeham et al., 2002). Sedimentological research revealed that the Upper Schöneck Formation investigated here (well Osch-1) locates in a slope facies during deposition and it contains much higher TOC content (3–11%) compared with its counterpart layer in a basin floor facies (0.4% < TOC < 2.5%) which was presented in well Obhf-1 by Schulz et al. (2002). The differences in TOC contents are not caused by maturation, as the Schöneck Formation in well Obhf-1 is at early oil window maturity (Ro = 0.51–0.59%; Schulz et al., 2002) and the TOC consumption on such marine shale is anticipated to be very limited (at maximum 1%) at this stage of maturity (Jarvie, 2012). In contrast, it is more likely that the upwelling brought dissolved nutrients from deep and cold bottom water to only the coastal area and led to a significant biota (e.g., diatoms) flourishing and an expansion of the oxygen minimum zone near the shoreline. As a result, organic matter with higher HI values has been preferentially preserved in the investigated proximal Upper Schöneck Formation compared with deeper facies. In addition, the sedimentation rate in an upwelling system is typically higher in a coastal-parallel ribbon than in a nearby or outer facies (Suess et al., 1987). Such a spatial black shale architecture has been demonstrated for the Upper Schöneck Formation which reaches its maximum thickness in a narrow belt parallel to the palaeo-shoreline (Sachsenhofer and Schulz, 2006).

Besides the described upwelling hypothesis, an increase in global sea water salinity and a decreased carbonate mineral deposition can also be induced by the global cooling event and can further influence the development of petroleum source rocks. Pore fluid measurement of the chloride concentrations and oxygen isotopic compositions of Ocean Drilling Program cores revealed that the deep ocean water salinity was obviously enhanced in response of Last Glacial Maximum (Adkins et al., 2002), because significant amount of freshwater was trapped in the polar ice sheet. A recent study revealed that the reduced atmospheric temperature is also responsible for the enhanced ocean stratification in the North Atlantic during the last glacial maximum (Jansen, 2017). The increased salinity and water stratification thus favour organic matter preservation. The global temperature drop in sea water would also increase the $CaCO_3$ dissolution, and thus decrease the proportion of carbonate minerals in the deposits. For example, geological records manifest that the CCD in the Pacific Ocean was deepened for more than 1 km near the Eocene/Oligocene boundary (Coxall et al., 2005). In the case of the Molasse Basin, the water depth during the deposition of the Schöneck Formation was between 400 and 800 m (Dohmann, 1991) which is far shallower than the average CCD (3.5–4.5 km) (Bickert, 2009). Nevertheless, the transition from the Lower Schöneck marlstone to the Upper Schöneck carbonate-free shale, which typically contains higher organic matter than marlstone, might be influenced by the temperature change in addition to the water level fluctuation. It needs to be pointed out that the development of the Upper Schöneck Formation does not exactly coincide with the E/O boundary (Fig. 2). This is caused by the delayed response of the sedimentary record from the global temperature change which can also observed in central North America (Zanazzi et al., 2007) and in the Central-Carpathian Paleogene Basin (Sotak, 2010) during the E/O transition.

Contemporaneously deposited with the Upper Schöneck Formation, there are many other effective marine source rocks developed right after the Antarctic glaciation all around the world, e.g., the Jenam formation in Surma Basin (Bangladesh) (Curiale et al., 2002), the Shahejie formation in Bohai Bay Basin (China) (Li et al., 2003), the Heath formation in Talara Basin (Peru) (Fildani et al., 2005), and the Maikop group in Eastern Paratethys realm (Sachsenhofer et al., 2017). These would imply that the correlation between the E/O global cooling event and the development of excellent petroleum source rock is not merely a coincidence in the Molasse Basin, but may exist in a wider area all over the world.

6. Conclusions

The Schöneck Formation and Dynow Formation are marine to brackish deposits with great petroleum generation potential. With the aid of the PCA based biplots, the systematic differences in TOC, HI, and Tmax are actually controlled by palaeoenvironment and precursor.

The biplots can not only figure out the correlations of two key factors among numerous variables, but also enable to elaborate meaningful parameters which are combined from multi-factors, e.g., MTTC*OL index. The correlative information provided by the biplots enables quick evaluations on how petroleum generation features are controlled by palaeo-environmental factors.

The global cooling event at the E/O boundary might have played a very important role in favouring the development of excellent petroleum source rocks by triggering upwelling, increasing sea-water salinity, and decreasing the carbonate deposition.

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Appendix A. Supplementary data

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